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The Warfighter Associate: Objective and Automated Metrics for Mission Command

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The Warfighter Associate: Objective and Automated Performance Metrics for Mission Command

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It has been assumed that within Mission Command and Network Enabled Operations information superiority results in greater information sharing, situational awareness, collaborative decision-making, and agility; all of which ultimately contribute to greater mission effectiveness. However, demonstrating the truth of these assumptions requires objectively measuring individual and collaborative Soldier performance and information sharing in networked environments, which is an enduring challenge. The Warfighter Associate (WA) is an Intelligent Agent software system that uses doctrinally-based knowledge engineering to offer decision-support for Soldier cognitive workflows. The underlying knowledge representation can serve as state traces, measuring aspects of Soldier cognitive performance across scenario runtime as dynamic events unfold on the battlefield. This approach can unobtrusively and automatically capture aspects of Mission Command performance over time. Specifically, the WA currently captures the following performance metrics:

1) **Objective cognitive workload over time**
2) **Responsiveness to events in dynamic environments**
3) **Course of action**
4) **Staff collaborations and manifest agility**

Our approach captures Soldier's goals and the plans to achieve those goals in *real-time* as the work dynamically unfolds as a complex network of cognitive tasks. The capability of an analyst to record, view, and analyze work activity dynamically and unobtrusively over specified epochs of time is, to our knowledge, unprecedented.

I. INTRODUCTION

Military operations are inherently complex human endeavors. Army commanders and their staff collectively face difficult and stressful challenges in managing battlefield operations. Warfare is chaotic and incredibly complicated, and resolving the attendant ambiguity of the battlefield is a cognitive challenge of the first order. At critical times, Soldiers are under tremendous pressure to quickly analyze overwhelming amounts of incomplete and sometimes contradictory data and to make decisions that have immediate impacts to mission success and human life. The consequences of those actions are not always intuitive or predictable.

The increased complexity of today's operational environment presents additional challenges. Advances in networking technology have transformed the way that Mission Command networks function. Mission Command operations involve large, interacting, and layered networks of staff personnel communicating across echelons of command. Operating in such a broadly collaborative and information-rich environment has the potential to confer unprecedented advantages in directing and responding to battlefield events (National Research Council, 2005); however, it can also present a number of

challenges. Current operational environments are challenged by the shift to multifaceted civil-military operations with joint, interagency, and multinational partners and the overabundance of information available across Army networks. In spite of Mission Command's profound dependence on networks, fundamental knowledge about the conduct of network-enabled communication operations is lacking, especially at the cognitive and social levels. The dependence of the Mission Command staff on robust interaction of networks is clear from its transformation to network-enabled operations (Alberts & Garstka, 2004; National Research Council, 2005).

The Challenge of Network-enabled Operations

The transformation of U.S. and NATO countries to network-enabled operations (NEO) has proceeded under a conceptual framework of network-centric warfare with four main tenets (Alberts & Garstka, 2004):

- A robustly networked force improves information sharing and collaboration
- Such sharing and collaboration enhance the quality of information and shared situational awareness
- This enhancement, in turn, enables further self-synchronization and improves the sustainability and speed of command
- The combination dramatically increases mission effectiveness

These four tenets capture the current challenges and goals of the Army transformation. However, they are in need of systematic study. For instance, it may be the case that information sharing in NEO has increased the quantity but not the quality of information. Indeed, today's battlefield commanders and staff are inundated with huge amounts of information/intelligence that are transmitted and stored across increasingly sophisticated Army networks. In response to the complexity of the battlefield environment, the current impulse and design of technical systems is to gather and process more and more information (Lynch, 2008). One concern is that such a data rich environment can quickly overwhelm and paralyze human decision-making capacities. Another concern is that human cognition is being reduced to managing complex computer databases and configuring displays, at the expense of engaging higher-ordered human faculties of critical thinking, sense making, and reasoning about the battle-space. A Vietnam-era commanding officer, COL Ted Fichtl (retired) who recently observed Mission Command at a Division and Brigade level US/UK coalition exercise, turned aside and remarked, "My God! They've taken the thinking out of Mission Command!" (Fichtl, 2010).

Managing the convergence of people, information, and technology—a *sociotechnical system* (Walker, et al., 2009) — is a defining challenge of our era. Despite the best intentions of solution providers there are inevitably situations where systems' capabilities are not in complete alignment with Soldiers' information needs. The inherent complexity and dynamic nature of military operations entails an unbounded problem space: all possible intricacies involved in the dynamics of the mission command space and the interrelationships of technical systems are difficult to predict in advance.

Objectively measuring Mission Command effectiveness is a formidable Army challenge. Researchers have difficulty capturing the intricacies of individual and team cognition, particularly as Soldiers confront environmental challenges with multiple overlapping problem spaces. How to develop predictive performance-based models of such emergent problem solving behaviors is an open problem in need of solutions. One such solution is automated collection and aggregation of empirical data derived from field or laboratory studies. An important research objective is to develop the scientific experimental

infrastructure and measures to capture Mission Command effectiveness, focused on theory development, experimentation, hypothesis testing, and data collection relevant to operations.[1]

An Experimental Infrastructure for Mission Command

In this paper, we demonstrate a novel approach for the evaluation of Mission Command performance using automated real-time, network-based measures of team cognition and team effectiveness. Our approach uses the state trace of activation of a prototype intelligent software agent technology— the Warfighter Associate— to model specific user workflows in response to unfolding events on the battlefield over the course of a military scenario.

The Warfighter Associate (WA) is an intelligent decision support tool under development for Mission Command that considers user intent, state of the world, and domain specific knowledge to recommend a course of action. The WA seeks to improve Mission Command performance by shortening the cycle time from data gathering to decisions. It uses a doctrinally-based knowledge representation to model role-specific workflows and continuously monitors the state of the operational environment to enable decision-support, delivering the right information to the right person at the right time.

We tested the WA over the course of a military scenario, demonstrating how unfolding events on the battlefield activate WA mission concepts, user goals, and the plans to achieve them. Capturing the state trace of WA knowledge activation over scenario runtime constitutes an important research breakthrough in that it contributes to the development of objective metrics for assessing Command and Control (C2) effectiveness. The most recent version of the WA includes an analysis tool to visualize mission concepts, tasks, and task performance in real-time. Based on novel quantitative metrics derived from the state traces of knowledge activation in the WA, we can operationally define important cognitive and Army concepts such as cognitive workload, multi-tasking, task completion timing, force synchronization, information sharing, and decision quality. This constitutes a potentially important methodological breakthrough in capturing objective group performance. Metrics are essential to developing, evaluating, and improving soldier-system interfaces and performance; and in our case, can also be collected unobtrusively. In sum, we describe an associate system that supports the full sequence of "data to decisions" to ensure that it occurs in a timely and accurate manner, and provides a novel class of metrics to assess the operational efficiency of mission command.

II. OVERVIEW – THE WARFIGHTER ASSOCIATE SYSTEM

The Warfighter Associate is an example of a knowledge-based system, an intelligent agent technology that uses collective knowledge from military doctrine, subject matter experts, and other information sources (see Arkerkar & Sajja, 2011). Compared to other types of AI technology, knowledge-based Associate Systems offer a high degree of flexibility, rationale for recommendations rooted in knowledge and available information, and a *proactive* and *reactive* manner of operation. Ultimately, these three characteristics are necessary for an AI system to be responsive to the uncertainty and complexity of information on today's battlefield and systematically tailored to staff workflows and the unit's standard operating procedures.

To make timely and optimal recommendations, the WA uses collective knowledge from doctrine and

[1] This statement reflects the out-brief recommendation by Working Group #4 (Analysis of Human Decision Making in Networked Environments) in a workshop by the Military Operational Research Society (MORS) entitled "Joint Framework for Measuring C2 Effectiveness" held at the Johns Hopkins University Applied Physics Laboratory in Laurel, MD (23-26 January, 2012). http://www.mors.org/events/2012c2.aspx

subject matter experts to infer human intention (goals) and reason about the best manner to achieve them (plans) given the state of the world (operational environment monitor).The WA is flexible; it is a plug-in capability, and the WA knowledge is independent of the system it is integrated with. Thus, the system can run as a stand-alone application, or can be lightly and seamlessly integrated with current or future systems.

The WA has a minimal level of automation (see levels of automation by Parasuraman, Sheridan, & Wickens, 2000), suggesting a set of specific courses of action but ultimately the decisions and actions are up to the Soldier. Rationale for the suggestions is provided to the Soldiers, for instance: the closest and best available intelligence, surveillance, and reconnaissance (ISR) resources in responding to a battlefield event based on a combination of availability, distance, speed, and capabilities. Transparency is a key system design if recommendations are to be accepted, selected, and acted upon by human operators (Parasuraman & Riley, 1997).

An Associate System is software driven by domain knowledge that is designed to assist a human operator. It can enable the Mission Command staff to engage in a high operations tempo by understanding their own decision cycle and reacting or pre-acting to their goals and by gaining possible insights into higher order effects and unintended consequences. A relevant paradigm for Mission Command is the late Colonel John Boyd’s concept of the “OODA Loop” (Boyd, 1986; see also Polk, 1999) where OODA stands for Observe-Orient-Decide-Act. The OODA loop defines a process by which an individual or team responds to a situation, with the need to repeatedly make decisions in light of dynamic events, and is closely related with the concept of Situation Awareness as developed by Mica Endsley (see Endsley & Garland, 2009). For our purpose of supporting decision-making, Boyd’s theory is central in defining the essential cognitive cycle and collaborative dimensions of Mission Command *performance*, particularly in relation to an adversary.

The Mission Command work domain is an obvious candidate for computer support. The demands to human information processing, which involve observing and monitoring communication streams, as well as organizing, combining, and evaluating data and intelligence, can quickly overwhelm cognitive capabilities. The Associate can filter through vast amounts of data looking for information of importance to the user based on the user’s intent. It does so by making abstract and aggregate conclusions about the state of the world in a more automated fashion, which in humans normally requires both attention and expertise. As information is being assessed, the intelligent agent can help in the development of basic and advanced situation awareness, including the identification of patterns, correlation of different data, diagnoses, problem solving, and even goal setting. It can present to the user the “best” solution to this problem based on currently available information, but support the user if a different course of action is chosen. In the action part of the cycle, the associate may be authorized to perform many of the routine tasks that could distract the user from the important events occurring. An Associate System also observes the actions undertaken by a human operator, combining those actions with the state of the world to determine the operator’s current objectives and activities. Based on the assessment of the state of the world and the activities and objectives of the human operator, the system can, within the bounds of its authority, carry out activities on behalf of the user, make the user aware of events particularly relevant to his activities, recommend courses of action, and manage the information content of the user’s displays.

The Warfighter Associate (WA) is intended to be a smart and seasoned assistant to the human user, designed to follow the human’s lead, aiding whenever necessary without the need for explicit instructions and within its bounded discretion. The human user preserves all opportunities to interact normally and perform all system tasks completely manually. The goal of the Associate System is to foster the functional integration of the sociotechnical Soldier-system.

III. WARFIGHTER ASSOCIATE ARCHITECTURE

The WA is a software system that models tasks and task performance in complex real-time operational environments. The WA can be used both as a decision aiding system and as a normative model of task selection and performance by human users. It is composed of a set of functions that create a closed loop cognitive engine that uses explicitly declared knowledge bases to perform situation assessment, dynamic planning, action execution and coordination across multiple actors.

The Warfighter Associate cognitive model has the following components:

- Domain-specific knowledge
- The ability to accept situational data as input data
- The ability to accept user actions as input data
- Algorithms to assess user actions, situational data, in accordance with the domain knowledge and do one or more of the following: provide notifications, provide suggestions, or perform system actions

As a brief example, given a reported improvised explosive device (IED) event, the associate system provides to the user— here, an intelligence officer (S2)—a recommended list of nearby surveillance assets that could be repositioned to quickly provide eyes-on the event location. The associate system's knowledge representation 'knows' that in response to an IED event this user will likely want to reposition known nearby surveillance assets with particular known capabilities. The term 'known' indicates that the associate system is aware of the current state of the world such as the position and capabilities of the available surveillance assets. In this manner, the associate system is proactive in aligning the likely goals and decision-making authority of the warfighter with the means to achieve them.

A key to understanding the mechanics of the associate systems is to think of the gears of the process as a *user intent interpretation* engine. Observed actions drive the intent interpretation capability of the Associate. By observing the Warfighter's actions, the Associate can interpret which scripts the warfighter is following, allowing it to refine its user intent representation— the set of active plans and goals— so that it can support the warfighter based upon his actual intent, even if that intent differs from the associate's recommendations. Specifically, the capability to model the knowledge used to represent the decision making process and to drive the behavior of the Warfighter Associate is provided by the Velox® Intelligent Software Suite. Figure 1 is a diagram of Velox®.

There are two interrelated knowledge representations in the Warfighter Associate: the Observe-Orient (O-O) graph, the Decide-Act (D-A) graph, and scripted plans that encapsulate procedural knowledge. The first of the two main distinct knowledge structures is the Observe-Orient (O-O) graph. The O-O graph represents general and situational knowledge about the current world-state ("who," "what," "when," and "how-much"), and linkages among beliefs (concepts) represented. The O-O graph provides a means for distinguishing between beliefs about the state of the environment and its true state. Beliefs are dynamically updated as a result of observations in the form of incoming data about the perceived state of some aspect of the environment; the updated situation awareness influences the Associate's purposeful interactions with the environment through the O-O graph. The links between the beliefs contain instructions for computing higher level aggregations and abstractions contained in each "child" belief from the data contained within each "parent" belief. Uncertainty calculations may also be

contained in the links, allowing different sources of information to receive more or less influence in shaping a belief value.

The second knowledge structure is the Decide-Act (D-A) graph, which is a graphical depiction of the hierarchical task structure in the system being modeled. This structure allows a principled separation between the intended future state (goal) from the means through which that goal might be attained (plan). It supports plan generation and plan recognition in dynamic, uncertain environments. A collection of goals and possible plans for achieving each goal makes up a course of action for a group. The D-A graph is defined to represent the alternative ways that goals can be achieved, so each plan child of a goal is a possible means to achieve the parent goal. Plan nodes are then decomposed into sub goals, with decomposition in this manner continuing until the level of basic interactions is reached in the

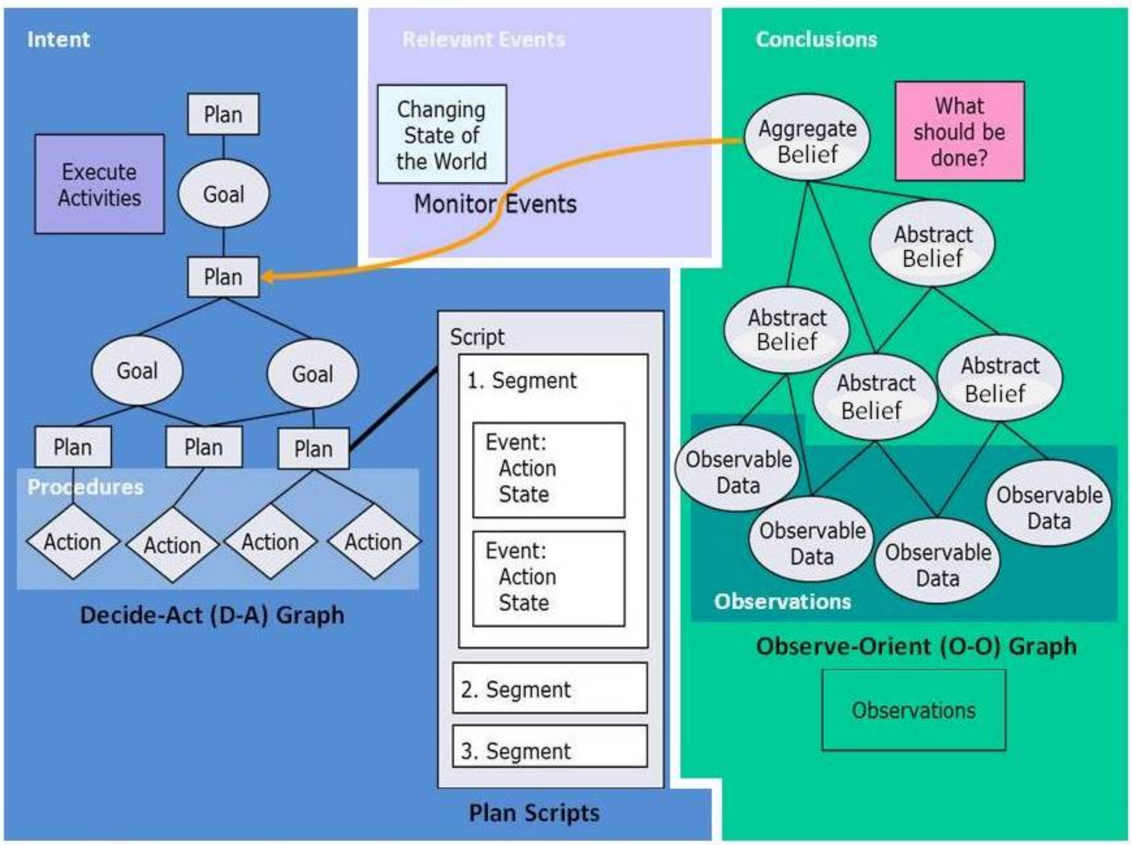

Figure 1. Velox® Intelligent Software Suite with Observe-Orient and Decide-Act Graphs

form of scripts. AD-A graph may provide for the intentions of many types of groups within a model. By observing the human's actions, and interpreting them in the context of the task models in the D-A graph, the Warfighter Associate can infer the human's intentions by explaining them in terms of implied plans for achieving shared task goals.

To provide dynamic behavior to the model, nodes (Beliefs, Plans, and Goals) have dynamic life cycle states. In the Observe-Orient (O-O) graph, life cycle state represents the prominence of a belief, allowing beliefs that are no longer supported by evidence to become forgotten. The feasibility and desirability of any particular course of action (path through the Decide-Act graph) may depend on what the group believes about the environment and what stage of development the group is in (O-O graph). To

implement the dynamic connection between the state of the environment and the possible courses of action, the model framework provides a belief monitoring mechanism. For example, a high-level plan “to survive” may subscribe to messages about threats. If an IED is reported, the subscription monitor will fire, triggering planning. The group may consider multiple ways to accomplish a goal to diffuse the IED. The specific way selected will activate monitors for the relevant information in the O-O graph. For example, a plan to use the 2nd Explosive Ordinance disposal platoon will monitor the O-O graph for obstacles on the route between the platoon’s location and the location of the IED. If a conditional statement in a monitor is found to be true, the detected event may be used to transition a plan or goal to a different life cycle state. In this way, plans and goals that are no longer feasible or desirable can be replaced with more desirable ones as the state of the beliefs change over time.

The Warfighter Associate decomposes high-level, abstract plans into lower-level, more concrete plans. Eventually, all decisions are made, and a plan can then be executed by running a script. Scripts contain actions and logic to determine when each action is appropriate. Actions, which are manipulations of the world state, can be performed by the Associate (“performed action”) or executed by the human and observed by the Associate (“observed action”). Since Associates are mixed-initiative, whether an action is performed or observed can be determined during runtime. Examples of actions include calling a route planner, querying a database, or re-tasking an asset. As a key part of the OODA loop, actions, by their definition, change the state of the world, which causes the O-O graph to be updated. This may result in re-planning, which may then cause additional actions to be performed.

IV. WARFIGHTER ASSOCIATE KNOWLEDGE

Knowledge-engineering tools are used in developing and maintaining the O-O and D-A graphs and the associated plan scripts. These tools enable doctrinal and Subject Matter Expert knowledge to be easily entered and put into a format where it can drive Warfighter Associate behavior. The knowledge comes from approximately twenty different Army publications, as well as subject matter expertise in response to high-intensity events such as IED detonations, medical evacuation (MEDEVAC) operations, high value target (HVT) sightings, Restricted Operating Zone (ROZ) establishment, and so on.

As currently developed, the Warfighter Associate is able to respond to:

- All normal doctrinal operations
- TIC
- Personnel recovery / downed aircraft
- MEDEVAC and casualty evacuation (CASEVAC)
- IEDs, including vehicle-borne (VBIED), suicide-vest (SVIED), and potential (P-IED)
- Indirect fires (e.g. mortar attack) with point-of-origin (POO) and point-of-impact (POI)
- Restricted operations zone (ROZ) for airspace de-confliction
- High value targets (HVT)
- Intelligence Surveillance Reconnaissance (ISR) asset management
- Unit boundary coordination
- Joint and coalition coordination
- Minefields
- Civilian demonstrations
- Air threats
- Small Arms Fire

The Knowledge Engineering tools that are part of the Warfighter Associate enable doctrine or subject matter expertise to be added or modified within the knowledge base without requiring any changes to the underlying software or system architecture. The O-O and D-A graphs sit on top of the associate architecture and thus are readily modifiable, for instance to tailor the knowledge to a Commander's standard operating procedures or to evolving threats on the battlefield.

The Warfighter Associate provides a dynamic real-time model of human intention and provides mission command with the ability to engage in high up-tempo operations with support for planning and plan execution and fault tolerance. It fosters rich human-computer collaboration and addresses the complexity of mission command in a network-enabled operational environment.

V. METRICS FOR MISSION COMMAND

The underlying activation of the knowledge structures in the Warfighter Associate can provide a dynamic real-time model of human intention that has the potential to support the analytical community with novel classes of metrics. This addresses the long-standing problem of objectively measuring mission command effectiveness at the individual and team level. These metrics can be derived from the pattern of node activations from the knowledge-base (O-O and D-A graphs) and used to gauge the effectiveness of the mission command staff.

Examples include:

- Cognitive workload (number of concurrently active goals across time)
- Currently active plans & goals
- Timing to complete tasks
- Necessary collaborations (shared plans & goals)
- Force synchronization (timeliness of distributed sub-goal satisfaction)

Since the knowledge includes a dynamic model of the operational environment, and the user interface is updated with appropriate alerts, suggestions, and highlighting of critical information as time progresses, the knowledge representations serve as *state traces.* The state traces depict the cognitive work demands on the mission command staff across scenario runtimes as dynamic events unfold. A suite of data analysis tools (DAT) was developed to look at the underlying node activations in the knowledge structures, which include an instance viewer, a log analyzer, and a shared event analyzer.

Data Analysis Toolset

The DAT has four primary components that are used to view node activations and a log output of moment-by-moment changes in activation states:

1) Heat Map: Active nodes in the knowledge structure which provides a heat-map for cognitive work analysis
2) Cognitive Workload Chart: Time-series figure of activation and deactivation of nodes which shows cognitive workload
3) Reports View and Task Completion Timing: The start and stop times for events, e.g., IED, TIC. Events include input data, alerts, recommended COAs, and actual COAs and are anything that triggers node activations and deactivations in the knowledge structures.
4) Shared Event Analyzer: Events can be shared across roles, requiring collaboration. For example, an air MEDEVAC requires coordination between the FSO, S2, and S3. The Shared Event Analyzer

measures collaboration (team performance) and force synchronization.

Cognitive Work Analysis Heat-Map

As shown in Figure 2, the *heat map* function allows one to view either current 'real-time' work activity (active nodes) in the O-O and D-A or alternatively, summed-up over a specified epoch of time. Often repeated goals, plans, and beliefs will have the highest activation and are depicted by the warmest colors. This snapshot of the work domain is useful in understanding and summarizing work activity as a constellation of activated goals and plans to achieve them and provides a detailed accounting of cognitive work activity across time. For example, this tool could distinguish between two individuals, one who sticks closely to an established and circumscribed work flow versus another individual who works dynamically and broadly across many different domain areas (i.e. collaborative multi-tasking).

There is a real need for descriptive and analytical models of how cognitive work is accomplished with both the attendant real-world complexity and the collaborative dimension of group decision-making. There are two modes of running the DAT, a real-time mode as the scenario run occurs, or a recall mode after the scenario run occurs. Also, the DAT can be used by multiple analysts to monitor multiple instances of the WA. These new prototype capabilities of an analyst to record and view work activity dynamically and unobtrusively (in real-time and over specified epochs) are, to our knowledge, unprecedented.

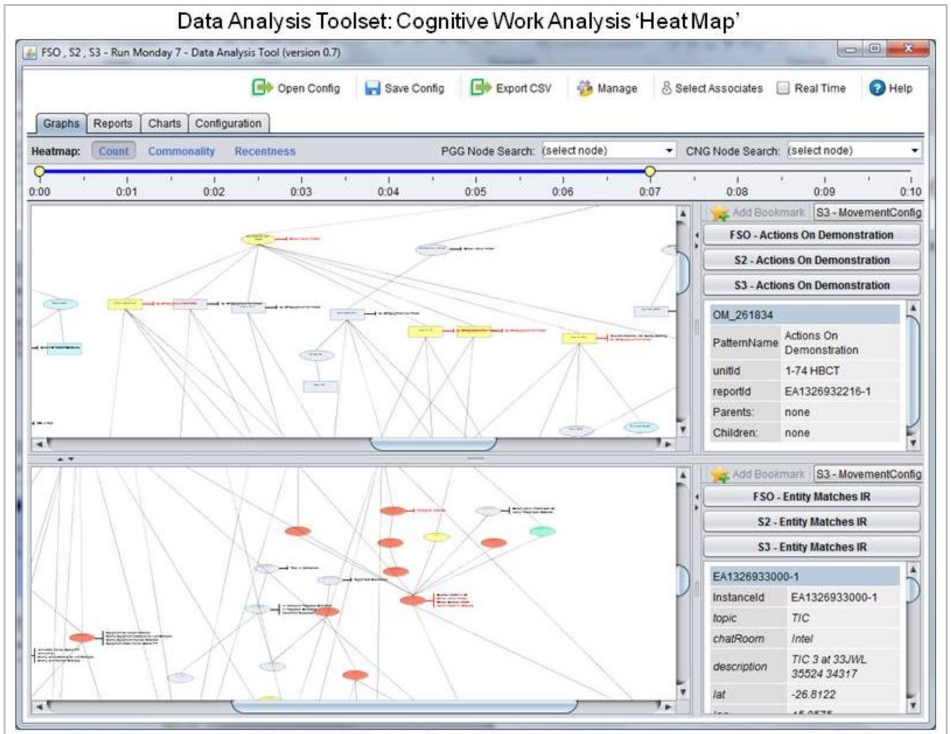

Figure 2: Cognitive work analysis 'heat map' of Decide-Act graph (top) and Observe-Orient graph (bottom) activations as the number of times each node was triggered across a specified time period, here the first seven minutes of the scenario data run as specified by the onset and offset bubbles of the blue time slider bar. This tool can also be used to observe currently activated nodes if the 'real time' box is checked in the top right. Warmer colors depict greater node activation counts; this is user configurable where numerical ranges can be specified and assigned to any selected color scheme.

Cognitive Workload Chart

Cognitive workload is the amount of demand on limited cognitive resources required to accomplish mission requirements for a human operator. The recognition of cognitive workload as an important aspect of behavior emerged from studies of work performance and subjective assessments of job demands (Wickens & Hollands, 2000; Wierwille & Eggemeier, 1993). Increasing job stress or performance pressure results in performance improvement up to a point. After that, increased job demands sharply reduce performance. This parabolic workload-performance curve has been widely-

established and is known as the Yerkes-Dodson relationship (Yerkes & Dodson, 1908). Importantly, it defines a zone of maximal performance. Cognitive workload fluctuates over time; in practice, this means that cognitive workload is a time-series that needs to be averaged over defined time periods that are short enough to allow detections of low, optimal, and peak workload states. The goal of managing Soldier-system interactions is to keep performance over time within the optimal region of performance. Note however, that performance is variable within an individual and overtime. The optimal region might fluctuate due to a host of intra-individual factors such as: fatigue, multitasking demand, stress, reduced attention span, etc. Nevertheless, being able to objectively measure cognitive workload as a time-series has practical utility in better aligning and achieving maximal Soldier-system performance, as well as better understanding intra-individual sources of variability. There are, however, no reliable, unobtrusive, direct measurements of cognitive workload. The current standard of measuring cognitive workload is the NASA Task Load Index (see Hart, 2006), which is a subjective survey method whose administration requires that one stop the field exercise or experiment. Recent direct measurements of brain activity suggest a path forward, but these methods are in the research stage and not fully mature technologies (see Dornhege, Millan, Hinterberger, McFarland, & Muller, 2007). Thus, currently unobtrusive measurement of cognitive workload cannot be performed under realistic operating conditions.

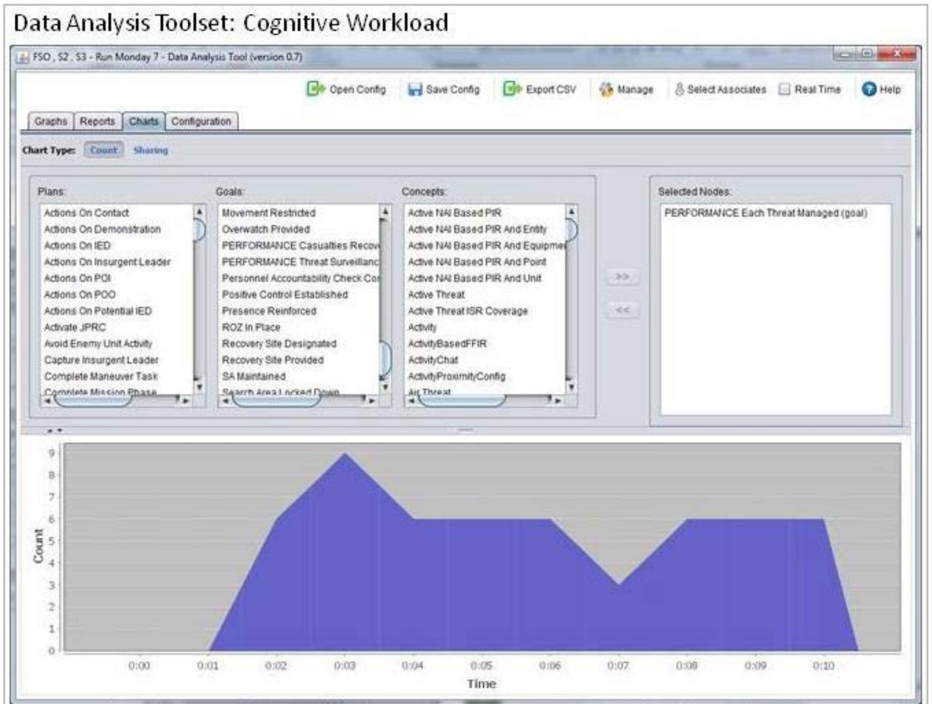

Figure 3: The activation of a specified plan, goal, or concept node can be observed across any period of the experimental scenario run. In this case, the goal node <Each Threat Managed> has been selected and the dynamics of node activation and deactivation (satisfaction) are shown across time.

Our formal metric construction of cognitive workload is derived from the activation of the user workflows in the D-A graph that is triggered from directly observable behaviors. Our measurement approach provides an *objective* and *time-series* measure of cognitive workload that is also defined by meaningful Mission Command behaviors. As shown in Figure 3, the instance viewer shows the number of concurrently active O-O and D-A nodes that are active either at a given point in time or across a specified time frame. This offers a useful measure of cognitive workload as given by the staff task demands at any point in time. In our case, we define cognitive workload as the number of concurrently active goals and sub-goals to achieve them. A limitation of the current approach is that not all goals are equally complex. Following the approach of Bierbaum, Szabo, and Aldrich (1989)— who developed a workload prediction model for piloting a UH-60 helicopter— it should be possible to derive estimates of the workload demands associated with each goal node in the D-A graph; thus assigning to each goal a level of difficulty that can be aggregated into a composite measure of cognitive workload.

Our metric is important as it offers an objective and continuous measure of cognitive workload that can be collected unobtrusively. It also has the advantage of being part of a system designed to provide decision-support. Node activations could provide an unobtrusive and continuous metric of cognitive workload that could then be fed into mission command systems as an estimate of user workload. System configurations (interface) and capabilities (alerts) could respond to this continuous estimate of user cognitive workload to achieve optimal Soldier-system performance.

Reports View: Data Capture and Behavioral Analysis

In scenario-driven military experiments/training-events, it can be challenging to precisely recreate and playback what happened during runtime, even with a solid data collection and analysis plan. For instance, it is difficult to establish the timeline of whether and when events occurred in a scenario-driven military training event, especially when unplanned interventions and schedule delays are introduced during execution time. Precisely capturing the timing of events and information flows is critical to enabling the military analytical community to advance a scientific capability to understand and address the challenges and complexities inherent in network-enabled mission command.

Data Analysis Toolset: Log Analyzer and Task Completion Timing

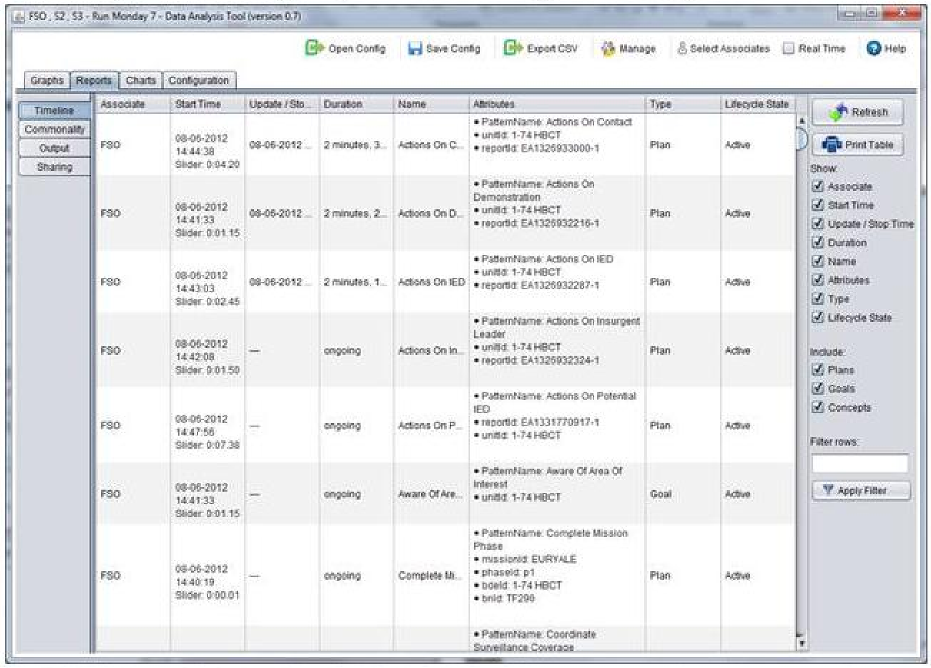

Figure 4: The log analyzer catalogs the Decide-Act (D-A) graph instance start and stop times, monitor events, and notification events for each running instance of the Warfighter Associate. The log files generated by the system can be filtered (right panel) in order to better understand Soldier-system performance and extract metrics of task completion timing, such as the onset and duration of critical battlefield events, resource allocation, and the timeline of information pushed by the Soldiers and the associate system.

The Data Analysis Tool addresses these challenges by capturing D-A and O-O graph instance start and stop times, monitor events, and notification events for each running instance of the Warfighter Associate. This is essential for defining performance. The Reports View is shown in Figure 4. With this tool the analyst can search the database generated by the Warfighter Associate system in order to better understand Soldier and system performance. The report can be filtered and sorted on number of dimensions (see Figure 4, right panel) to include: associate, start time, update/stop time, duration, name, attributes, type, and lifecycle state.

Based on the Reports View, key performance metrics include: operational tempo, resource management, and information flows. Performance can be defined in terms of operational tempo (task completion time), efficiency of resource allocation, tracking when battlefield events actually occurred during scenario run-time and when and what recommendations were given to the users. Operational

tempo refers to how quickly the staff is able to cycle through decision-making in effecting the battlefield. The Timeline Report provides task completion timing, the onset and duration (to goal satisfaction) of critical battlefield events. Resource management refers to how well the staff is able to coordinate and prioritize the use of limited battlefield resources. This is especially the case with Intelligence, Surveillance, and Reconnaissance (ISR) assets. The Warfighter Associate monitors the location and status of all assets in the battle-space and pushes recommendations; and all of this data is captured in log files and a database. Using the Reports View, an analyst can determine whether and when assets were tasked to assess efficiencies. Finally, the Log Analyzer gives access to the full timeline of information as it is reported or pushed on the network (i.e. chat room or voice communication transcribed to text) by the Soldiers and the Warfighter Associate system. This is essential for capturing and analyzing the complex information flows that occur in the Mission Command network.

Shared Event Analyzer

A shared event is defined as activated O-O and D-A nodes that are shared by multiple WA Instances, in our case by any combination of the S2 (Intelligence Officer), S3 (Operations Officer), and FSO (Fire Support Officer). The Sharing Report captures the time and content of each shared O-O and D-A node instance and displays a representation of the shared events between multiple WA Instances. This is illustrated in Figure 5 whereby the color of the D-A nodes (for the MEDEVAC hierarchical sub-tree) denotes unique or shared responsibilities. In this example, task responsibilities that are shared by all three role positions (S3, S2, FSO) are shown in grey, whereas those shared by the S3 and FSO in orange, and those unique to the S3 or FSO are in green and yellow, respectively. Two metrics can be derived from such a representation: collaborative information flows and force synchronization.

Collaborative Information Flows

Most tasks are not planned or executed in isolation, either in terms of other tasks or in terms of other actors and stakeholders. The essence of teamwork is the ability to efficiently maintain a coherent set of tasks across many actors and assets in a manner that does not conflict with one another. Geddes (1994) provides an analysis of conflicts across multiple actors and assets to identify two separate families of conflict: Goal Conflicts and Plan (or activity) Conflicts. Recognizing that both goals and activities are hierarchical in nature, this analysis explicitly addresses sub-goals and sub-activities and the differences between purposeful state changes (goals) and incidental state changes ("side effects") at different levels of activity aggregation and decomposition. As noted by the author, two plans that may seem perfectly compatible at one level of aggregation may have serious side effect conflicts at a lower level of decomposition that blocks their successful joint execution across the team. Geddes also makes the case that only some of the conflicts can be detected and avoided at "design time." From a systems engineering and behavioral research perspective, there is always a fundamental need for "execution time" conflict detection and correction across teams (Geddes, 2011).Our method of tagging collaborative information flows and the metric of *force synchronization* are tools that the analyst can use to assess teamwork during execution time.

The method of tagging collaborative information flows on the D-A graph (as input and output arrows) allows one to determine whether these staff processes were mutually supported during task execution. A sub-section of the D-A is illustrated in Figure 5. In this illustrated sub-section, the plan [Use Air MEDEVAC] is tagged with arrows where necessary collaborative information flows are represented. The FSO is responsible for responding to an air MEDEVAC request. The Warfighter Associate reads the MEDEVAC request from the chat-room input and then prompts the FSO by posting this request on their

graphical user interface. The arrow to the right of the [Use Air MEDEVAC] plan indicates that the WA shares this information with both the S3 and S2. The operations officer, S3, is responsible for all force protection activities of Soldiers and civilians in location of the designated MEDEVAC site. And if the MEDEVAC was induced by enemy activity, then it is important that the intelligence officer, the S2, provide actionable intelligence to the MEDEVAC crew on the enemy disposition in the area.

The illustrated sub-tree details mission concepts and staff workflows, such as designating and providing ground security for the recovery site as well as air security for the MEDEVAC. In satisfying the sub-goal <Ground Security Provided for Site> the plan [Task Unit to Secure Site] is activated if a unit is tasked to provide site security. The arrows indicate a necessary collaboration between the FSO managing the MEDEVAC request and the S3, responsible for establishing positive control over the designated recovery

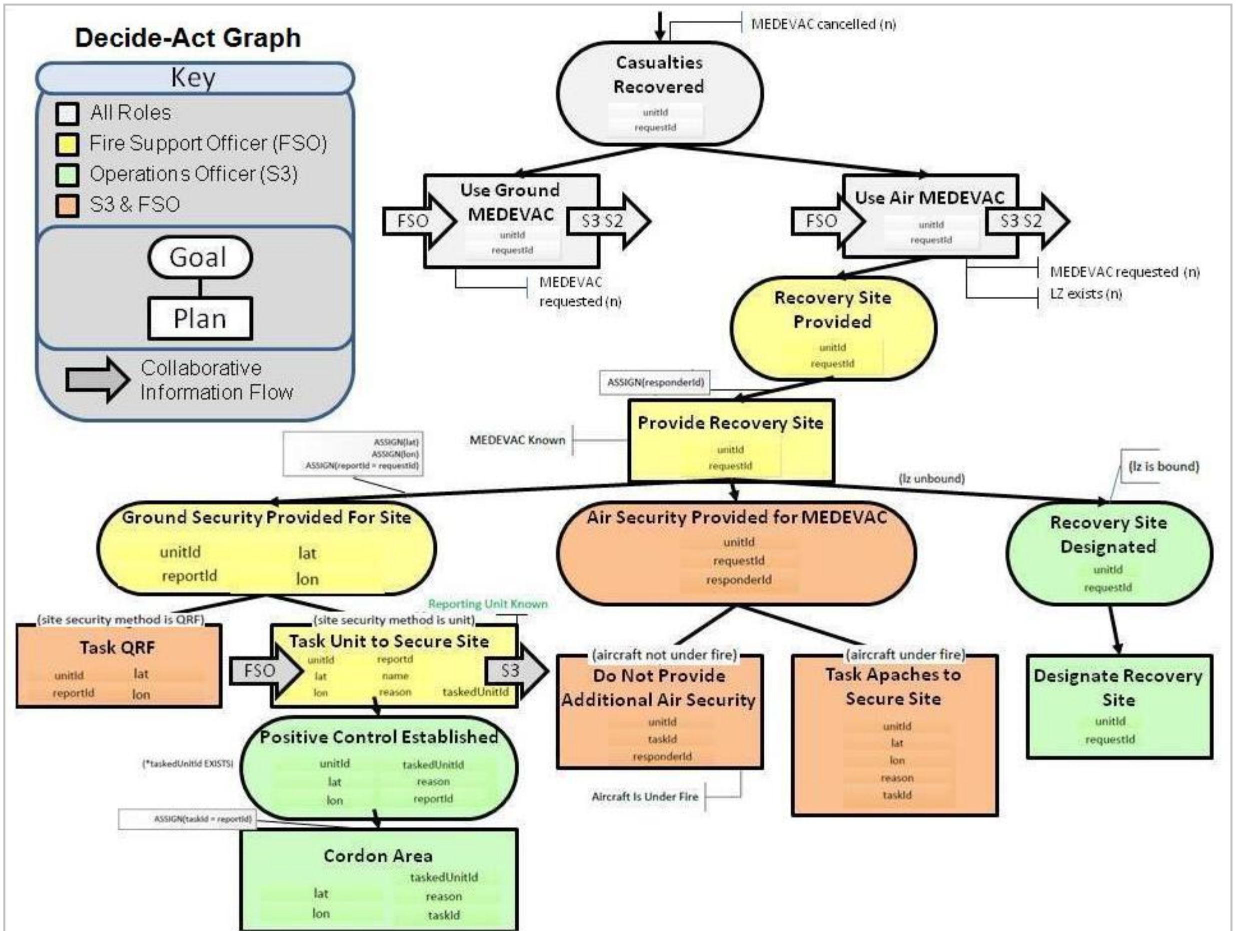

Figure 5: Illustrated Sub-section of Decide-Act (D-A) Graph Hierarchy for MEDEVAC Operations

site by cordoning off the area. In tagging the D-A with collaborative information flows, the Warfighter Associate actively supports collaboration. The analyst uses the Reports View toolset to determine whether mission concepts and staff workflows were indeed supported.

Force Synchronization

The metric of *force synchronization* attempts to measure collaborators' coordination of shared activities and purpose across time and space. The concept of *force synchronization* applies to groups of actors

that desire to arrive at a set of goal states by achieving a set of intermediate states in a specific sequence (Geddes, 2011). While the sequence of intermediate states is often described in terms of time and space, force synchronization can also refer to the synchronization of staff workflows along the social and cognitive dimensions. For example, in the case of Soldier-information systems, synchronization may involve communication and decision sequences with accompanying states of data and awareness. Synchronization exists by degree. Perfect synchronization can be said to exist when all of the actors achieve each of the intermediate states they are responsible for according to the expectations of the other actors and in a manner that does not create a conflict, either direct or indirect, between the actors (Geddes, 2011).And, synchronization is an integrative measure that occurs over a period of time rather than at an instant. As a result, there is a characteristic time period over which synchronization can be measured. The time period chosen for measurement should be long enough to capture the full time-series of shared activity.

Our metric definition of force synchronization is based on the timely co-activation of essential tagged D-A nodes by collaborators in response to shared significant events (e.g. battle drills) across a period of time. For instance, the timely response and satisfaction of an air MEDEVAC request requires that the staff quickly work through several collaborative sequences in tandem to satisfy several intermediate goal states, from designating and tasking units to secure the recovery site (S3), to establishing an air corridor and air security (FSO), to providing intelligence on enemy force disposition in the immediate vicinity and threats along the air corridor (S2).A staff with a high-degree of force synchronization can achieve their intermediate goal states in a timely manner that does not create conflict with one another. The Data Analysis Toolset allows the analyst to view the activation dynamics of the D-A graph and possibly identify friction points of collaboration that contributed to poor force synchronization, or simply assumptions and workflows that were overlooked. For instance, perhaps an inordinate amount of time was spent satisfying the goal <Air Security Provided for MEDEVAC>, or alternatively, perhaps the goal was not attended to, nor satisfied. The analyst would then be clued in to determine why that was indeed the case. Possible factors influencing force synchronization include the quality of task execution, situation awareness, shared understanding, and team collaboration. Continuing our example, perhaps the staff had an incomplete picture of enemy air threats and thus spent a considerable amount of time seeking information and then deliberating whether to request additional air security assets (e.g. Apache helicopters). Or alternatively, perhaps the staff did not challenge their assumptions and implicitly assumed the mental frame of no known enemy air threats. In sum, the activation dynamics of the D-A nodes provides the analyst with a state-trace of the collaborative workflows underlying our proposed metric of force synchronization and important markers to uncover the governing dynamics of staff collaboration.

VI. METHODS & EXPERIMENTAL SCENARIO

Our humans-in-the-loop experiment was conducted in our laboratory facility at Aberdeen Proving Ground and featured a finely detailed, high fidelity scenario scripting the actions of four battalions as well as host nation military and police units acting within an area of interest to a larger, parent military unit, a brigade. The level of analysis and agency in the experiment scenario was the brigade which included three soldier participants led by a senior non-commissioned officer (NCO) and two lower ranked NCOs. The senior NCO, a Staff Sergeant (E-6) with 10 years experience, assumed the role of an operations officer (S3). The other two NCOs were Sergeants (E-5) with 3 and 4 years experience who assumed the role of an intelligence officer (S2) and a fire support officer (FSO), respectively. The NCOs all experienced at least one combat tour under counter insurgency (COIN) operations in either Iraq or Afghanistan and were accomplished in their role-position. These soldiers were from the same organic unit, understood their

role positions, and performed well and cohesively within the combat vignettes of the scenario.

The experiment was conducted as a two-day event. The first day was devoted to reading the soldier participants into the scenario, which included a "road to war" briefing by the scenario co-author and officer-in-charge (Lieutenant Colonel, O-5). Soldiers were given a full dossier of information including intelligence summaries, preplanned fires, ISR synchronization matrices, and key coordinating maneuver graphics supporting their upcoming responsibilities. All three soldiers were knowledgeable of the mission command system used to maintain a common operational picture during the experiment, the Command Post of the Future (CPOF). Soldiers received three hours of training using CPOF to be assured of a base level of soldier performance using the system. The second day consisted of the four hour experimental run (interspersed with three 20 minute breaks or pauses) followed by an after-action review conducted by the officer-in-charge. The experimental scenario consisted of COIN operations and key events/threads included: (a) a host nation convoy transporting raw "uranite" fissile material through their area of operations, (b) finding, fixing and conducting a cordon and search operation versus a high value target (HVT), (c) a planned enemy attack on host-nation parade dignitaries using an improvised explosive device (IED), (d) responding to enemy mortar attacks, (e) supervising the repositioning of a critical radar asset, (f) missing ammunition, and (g) recovery of a downed civilian aircraft in a hostile border area.

Since the action took place within a brigade area of interest, the soldiers assumed responsibilities for the operation of a brigade tactical operation center (TOC). They performed several functions. First, they monitored the battlefield environment and Mission Command inputs via six chat rooms. Four of the chat rooms were organized by Mission Command function (maneuver, intelligence, fires, and sustainment), one represented Joint Special Operations Command and higher echelons of command (JSOC/HICON), and

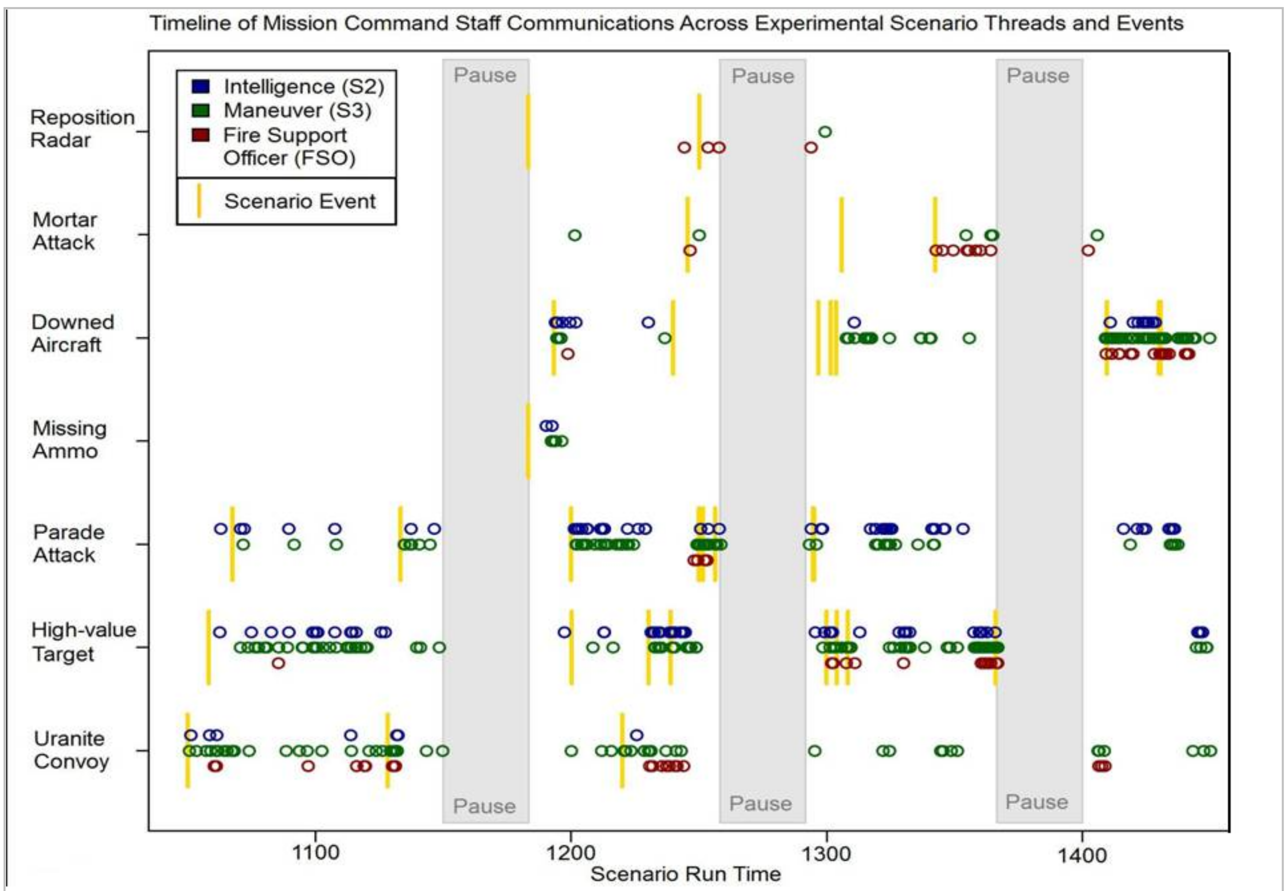

Figure 6: Timeline of voice and chat room communication activity by the Soldier participants— intelligence (S2), maneuver (S3), and fire support officer (FSO)— across the experiment sorted by scenario threads. Scenario-driven chat room inputs of significant battlefield information are depicted as yellow ticks. Experimental pauses are shown in gray.

another simulated liaison lash-ups with host nation units (Gorgasnet). Gorgas was the name given to the host nation. The experimental scenario (Buchler & Moyers, 2012) consisted of three hours of approximately800 scripted chat room inputs from over 40 scripted actors representing both routine chat room messages and those in response to scenario events. The experiment itself lasted four hours because of the three 20 minute breaks added during runtime.

Second, the soldiers processed all of the incoming chat room information and used CPOF to maintain a common operational picture (COP) of significant events occurring within their area of operations. Third, the soldiers interacted with the synthetic (i.e. scripted) actors in the chat rooms, for instance by requesting additional information, tasking subordinate battalion units, re-tasking ISR assets, coordinating with the host nation units, or issuing regular reports to higher echelons of command. Responses to requests for information were handled by an experimental team, the "white cell", who inserted inputs into the various chat rooms assuming the names of the various synthetic actors. Friendly unit locations were displayed on the COP to simulate the Mission Command functionality of Blue Force Tracker. The white cell also handled the movement of friendly unit icons around the COP to include the re-tasking of unit and ISR assets.

The Soldier participants each sat in separate sound attenuated experimental chamber in front of two screens, one populated with the inputs to the six chat rooms and the other with the CPOF Mission Command System that functioned as the brigade COP. The isolation from one another forced the participants to communicate via voice (headset) or the chat room interface. Voice communications were in a common channel.

The data recorded during the scenario experiment consisted of a log of all voice and chat room communications, screen video recordings, and the log output of Warfighter Associate. The three instances of the Warfighter Associate, one for each duty position S2-S3-FSO, were run in the background. This means that decision aiding was turned off and the recommendations generated by the system were not provided to the soldier participants. However, the Warfighter Associate did collect data during the experimental scenario, which was fed into the data analysis tool (DAT). During the experimental scenario, the white cell could observe in *real time* the metrics described in the next section, our results (see Figures 7 and 8).

VII. RESULTS

Timeline of Staff Communications

The experimental scenario proved to be quite challenging to the Soldier participants, requiring a high-degree of staff collaboration. Figure 6 provides a raw timeline of staff voice and chat room communications, sorted by experimental scenario thread and corresponding ticks of significant chat room inputs. The significant chat room inputs were often reports relayed into chat rooms by battalion operators in contact with subordinate units at the tactical level or collection managers of ISR assets. It is evident that the Soldier participants were challenged with dealing with multiple overlapping events. For instance, the communication pattern of the maneuver (S3) NCO suggests that he was able to successfully manage multiple communications threads about multiple threats as they occurred. In addition, the data also suggests that the maneuver (S3) NCO sustained attention to particular scenario threads such as the uranite convoy moving through the area of operations, perhaps indicating command relevance and prioritization of effort. Next, we used the DAT to examine the activation data provided by the WA system.

Cognitive Workload Results

The Data Analysis Toolset facilitates the analysis of the state traces of node activations captured by the WA system, which we use to develop a novel metric for cognitive workload to assess Mission Command performance. For the analyst, the utility of new metrics are determined by how well they capture meaningful staff performance. This depends on how well the WA system represents activated domain knowledge over the course of execution time. These results serve as a proof of concept and a concrete example of the utility of our metric framework and analytical approach using the WA system.

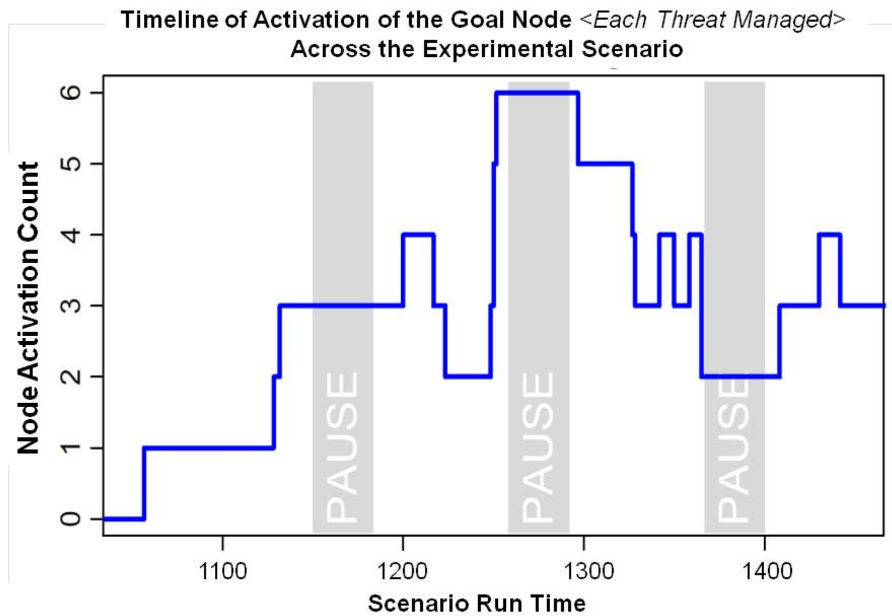

Figure 7: Timeline of the activation and deactivation (satisfaction) counts for a specific goal node <Each Threat Managed> depicted across the entire experimental scenario. The <Each Threat Managed> goal node is perhaps a good candidate for a measure of cognitive workload for the whole Mission Command staff.

In Figure 7, the activation count of one goal node from the D-A graph is depicted across the experimental scenario. This high-level goal node *<Each Threat Managed>* tracks current threats in the area of operations. As a metric, the activation profile of this high-level goal node represents the many different workflows of responding to threats. The activation count increases steadily as more and more compounding events occur in the area of operations. In representing the number of active workflows, the*<Each Threat Managed>* goal node is perhaps a good candidate for a measure of cognitive workload for the staff. Deactivations or satisfaction of particular instances of the goal node *<Each Threat Managed>* are depicted as well and occur when threats are successfully managed in the area of operations. The DAT can be consulted for a more precise accounting of exactly which threat was successfully managed at a particular time-step.

ISR Resource Management Results

Managing and prioritizing limited ISR resources is an important Mission Command function. Here we examine the activation count of a goal node from the D-A graph *<Threat Surveillance Adequate>* that is activated when an active threat exists in the area of operations and there is **no** ISR asset in range to cover the threat. The WA system monitors the current location of all known ISR assets and is knowledgeable of their capabilities. The *<Threat Surveillance Adequate>*goal is satisfied when an ISR asset moves in range to cover the threat, which typically requires that the staff task or re-task ISR assets. In Figure 8, the activation count of the *<Threat Surveillance Adequate>* goal is depicted across our experimental scenario. Note that for the first half of the experimental scenario (until around the 1230 time-step) the *<Threat Surveillance Adequate>* goal is efficiently satisfied, staying at zero. Afterward, the staff is unable to satisfy all the surveillance demands in the area of operations given limited ISR resources.

Manifest Agility Results

The time course of goal activation can also be rendered against a standard baseline of comparison. The dotted lines in Figure 8 reflect the time course of ISR needs across the experimental scenario *with no staff*

inputs meaning that the ISR assets remained static with no tasking or re-tasking. To arrive at this graph, the experimental scenario is run in a baseline condition—a *dry run* without staff involvement—represented by the dotted line. The experimental condition is then run with staff involvement given by the red line in Figure 8. This difference is a measure of what has been termed *manifest agility* by the Command and Control (C2) operational research community (Alberts, 2011). According to Alberts and Tillman (2012), manifest agility is defined by the response to an event that has occurred and this involves comparing what actually happened to what would have happened if no change had taken place. Thus, the goal activation dynamics depicted in Figure 8 reflect the manifest agility of the staff and in effecting ISR management.

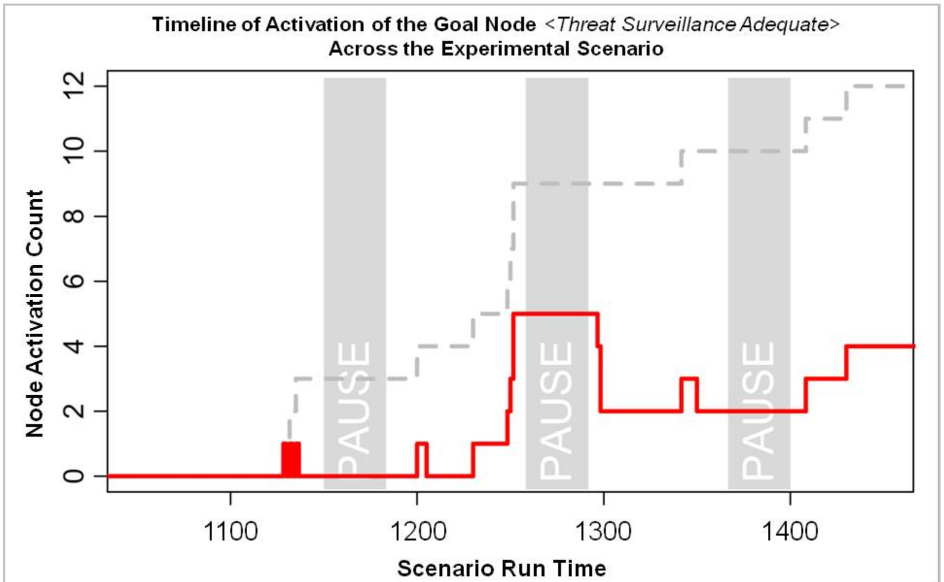

Figure 8: Timeline of the activation and deactivation (satisfaction) counts for a specific goal node <Threat Surveillance Adequate> depicted across the entire experimental scenario. The <Threat Surveillance Adequate> goal node is triggered when and there are no ISR assets in range of an existing threat in the area of operations. This is a measure of the allocation of ISR resources, which are perhaps limited in relation to the number of threats during the latter half of the scenario. The gray dotted-line represents a baseline *dry run* condition with no Soldier participation where ISR assets have not been tasked or re-tasked in response to scenario events.

VIII. CONCLUSIONS

Objectively measuring Mission Command effectiveness is a formidable Army challenge given the difficulty capturing the intricacies of individual and team cognition, particularly as Soldiers confront environmental challenges with multiple overlapping problem spaces. The WA system provides one possible metric solution by automating collection and the aggregation of empirical data derived from field or laboratory studies. The WA provides capabilities to improve and evaluate performance in Mission Command, including difficult to quantify concepts such as cognitive workload, resource management, and agility. Importantly, the WA also provides a computational instantiation of Soldier workflows, represented in the O-O and D-A graphs, from which to develop predictive performance-based models of emergent problem solving behaviors in complex collaborative environments.

An important future direction for this research is to validate these measures of cognitive workload and force synchronization in additional laboratory experiments and to scale-up this effort to capture data from military training events as field studies. The cognitive workload measure, for instance, could be compared to standard subjective measures, such as the point estimates of the NASA Task Load Index (Hart, 2006), as well as more direct measurements of brain activity. In the latter case, electroencephalography can be used to record and render a time series of electrical activity along the scalp. It would be very interesting to examine whether there exists a robust neural signature associated with the time course of goal activation, as inferred from the state traces of the WA.

Our metric approach can also be used to assess the effectiveness of any prototype technology. In this case the experimental design requires two conditions, one with and another without the prototype technology. Used in this way, the WA would simply run in the background and not contribute decision-support. Instead, the WA would provide the metrics framework for assessing staff performance with and

without the prototype technology. For the acquisition community, these metrics could provide solid benchmarks of performance to assess the effectiveness of any prototype technologies, such as a new mission command system, across the development cycle on a range of dimensional metric parameters.

One potential application of the WA is training technology. The alerts and decision aids offers Soldier's support in Mission Command and performance can also be evaluated and used during debriefings and after-action reviews. The WA could reduce training time, and thus training costs, while increasing Mission Command performance through situated practice in scenario-based training and in the application of doctrinal knowledge. In terms of practical utility, the WA also potentially addresses organizational and environmental challenges in providing decision-aiding to Soldiers whom are inexperienced, fatigued, or both.

In sum, the WA addresses a major tenet of the U.S. Office of Secretary of Defense's "data to decisions" initiative (Swan & Hennig, 2012) and the primary challenge for military commanders and their staff to shorten the cycle time from data gathering to decisions. The WA provides a novel class of metrics to assess the operational efficiency of mission command. Our approach may be an important development toward the goal of a mature scientific experimental infrastructure and the measures to capture Mission Command effectiveness, focused on theory development, experimentation, hypothesis testing, and data collection relevant to operations.

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